Polarized Tops from New Physics

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Tops and new physics at the LHC

- **Top quark physics a highly anticipated aspect of physics at the LHC**
  - top factory: SM $t\bar{t}$ production ~ 830 pb
- **New physics responsible for EWSB must have large couplings to the top**
  - Anticipate relatively large cross-section for associated production of top and new physics
- **New physics will couple differently to t_L, t_R**
  - $\Rightarrow$ net polarization of tops from new physics
  - polarization will depend on kinematics and chiral couplings
- **Polarization of tops from new physics probes chiral structure of new physics**

Polarization without reconstruction

- **Approach: study top polarization using kinematic distributions which do not require full event reconstruction**
- **With missing energy, event reconstruction requires assumptions about event topology**
  - Not necessarily desirable, especially in initial phases: new physics with stable invisible particles, complicated cascade decays
- **Hadronic tops: top can be completely reconstructed without information from the rest of the event**
- **Collimated tops: can construct variables which become independent of the top rest frame in the collinear limit**
  - works for *both* hadronic and leptonic tops

Hadronic tops

- **Angular distribution of daughter particles in top decays:**

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1 + \mathcal{P}_t\,\kappa_f \cos\theta_f\right)$$

- **'spin analyzing power' κ_f depends on particle identity:**
  - $\kappa_b = -\frac{m_t^2 - 2m_W^2}{m_t^2 + 2m_W^2} \simeq -0.4$
  - $\kappa_W = -\kappa_b$
  - $\kappa_\ell = 1, \qquad \kappa_\nu \simeq -0.3$

- **Hadronic tops: cannot distinguish $\bar{d}$ from u**
  - but: on average, $\bar{d}$ less energetic than u in top rest frame
  - $\Rightarrow$ form angular distribution of the softer light quark jet j
  - $\kappa_j \simeq 0.5$ (Jezabek, 1994)

Hadronic tops

- **Polarization-sensitive kinematic distributions for hadronic tops:**
  - take axis of polarization to be top direction of motion in the lab frame: net polarization $\langle \mathcal{P}_D \rangle$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}\left(1 + \langle \mathcal{P}_D \rangle \kappa_i \cos\theta_i\right)$$

  - b-jet angular distribution: $\kappa_b \simeq -0.4$
  - reconstructed W: $\kappa_W \simeq 0.4$
  - softer light quark jet: $\kappa_j \simeq 0.5$
- **Depending on the methods of event selection and top reconstruction in a given study, any or all of these distributions may be appropriate.**

Collimated tops

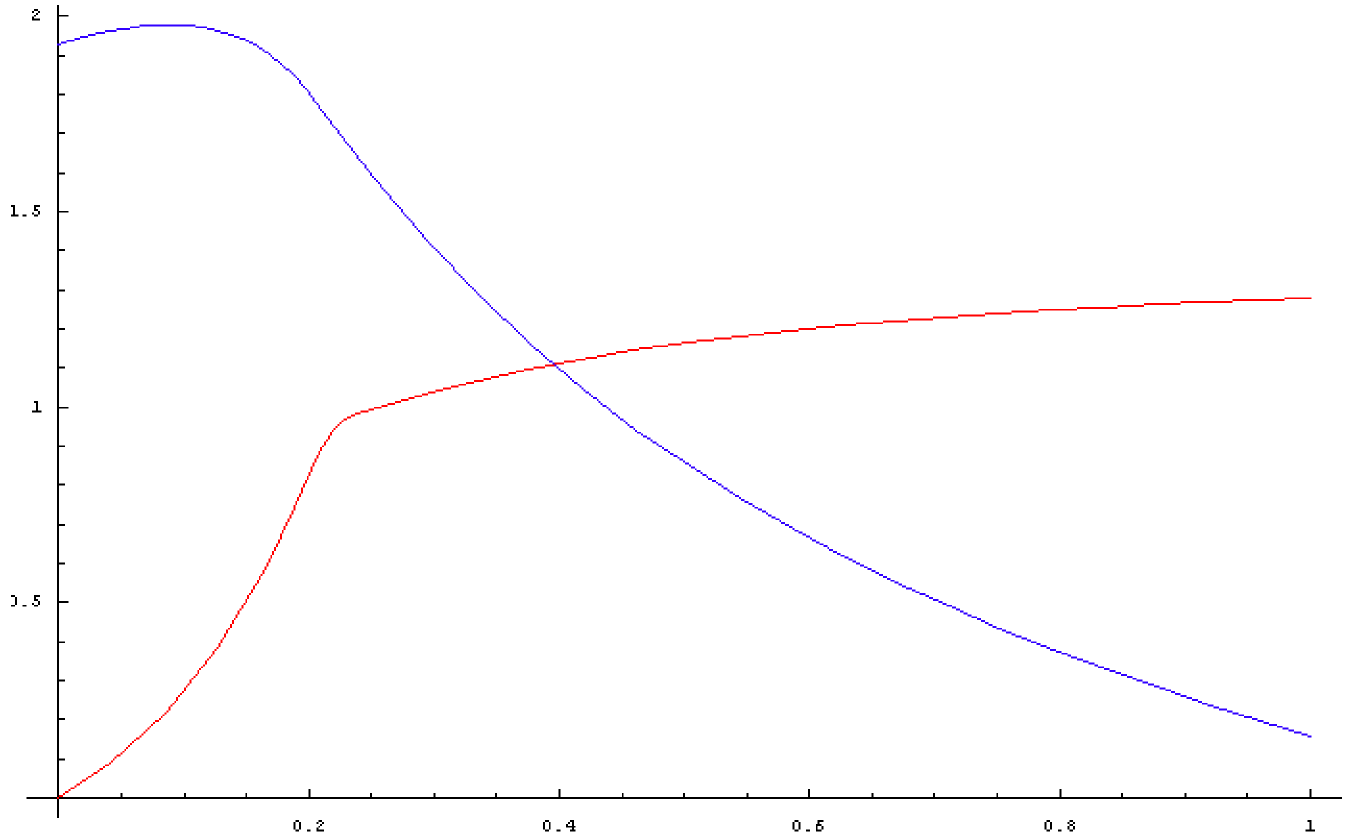
- **Tops from very massive new physics will be highly boosted, and their decay products will be collimated**
- **Hadronic tops: if b (or W) can be identified within top, then a natural variable is the fraction of lab frame energy carried by the b,** $z = \mathcal{E}_b/\mathcal{E}_t$
  - In collinear limit,

$$\frac{1}{\Gamma}\frac{d\Gamma}{dz} = \frac{m_t^2}{m_t^2 - m_W^2}(1 - \kappa_b\langle\mathcal{P}_D\rangle) + \kappa_b\langle\mathcal{P}_D\rangle\frac{2m_t^2}{m_t^2 - m_W^2}z$$

  - axis of polarization again top direction of motion in the lab frame
- **Leptonic tops: natural variable is fraction of visible lab frame energy carried by the lepton,**

$$u = \frac{\mathcal{E}_\ell}{\mathcal{E}_\ell + \mathcal{E}_b}$$

Collimated tops



Distribution of u for positive (red) and negative (blue) helicity tops.

- Measurable distribution a linear combination of positive and negative helicity distributions according to degree of polarization $\langle \mathcal{P}_D \rangle$

Polarization from cascade decays

- **Many well-motivated models feature cascade decays of the form (top partner) $\rightarrow t +$ (vector boson partner)**
  - decay produces polarized tops due to chiral couplings λ_L, λ_R
  - can compute net production polarization $\langle \mathcal{P}_P \rangle$ as a function of particle masses

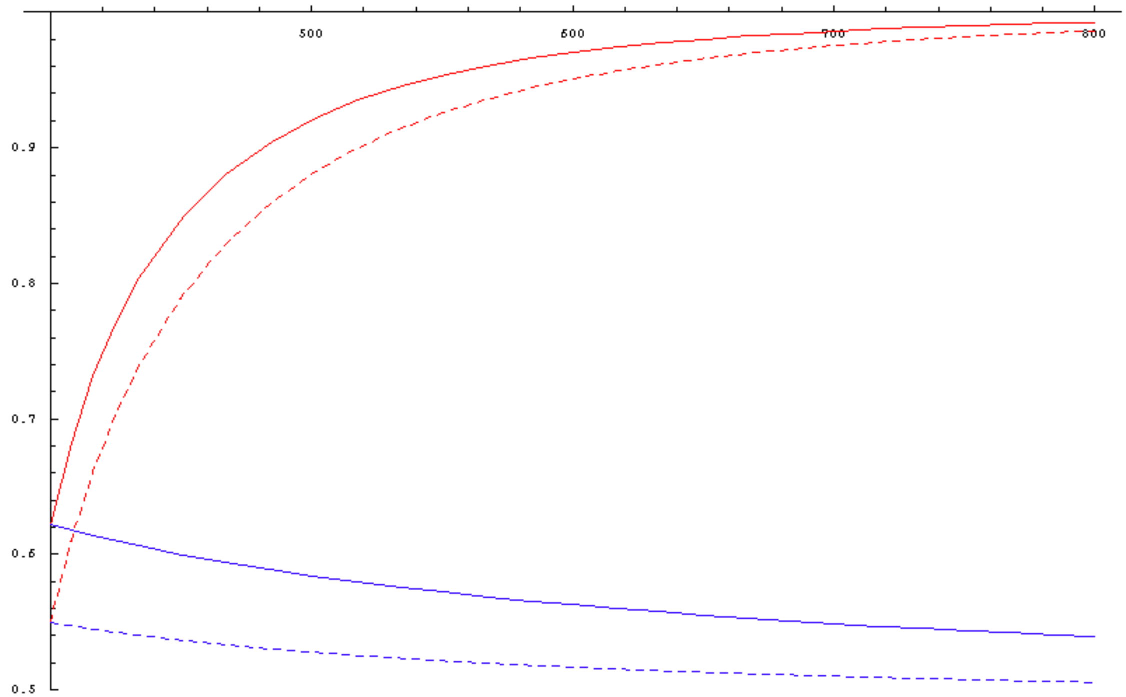
- **SUSY:** $\tilde{t} \rightarrow t\,\chi^0$

$$\langle \mathcal{P}_P \rangle = \frac{(|\lambda_R|^2 - |\lambda_L|^2) M |p_t|}{(|\lambda_L|^2 + |\lambda_R|^2)(M E_t - m_t^2) + 2\mathrm{Re}(\lambda_L \bar{\lambda}_R) m_\chi m_t}$$

- **Same-spin partner models:** $\hat{T} \rightarrow t\,\hat{V}^\mu$

$$\langle \mathcal{P}_P \rangle = \frac{(|\lambda_R|^2 - |\lambda_L|^2)|p_t|(M^2 + 2m_V^2 - m_t^2)}{(|\lambda_L|^2 + |\lambda_R|^2)(3E_t m_V^2 + 2M|p_t|^2) - 6\mathrm{Re}(\lambda_L \bar{\lambda}_R) m_V^2 m_t}$$

Polarization from cascade decays

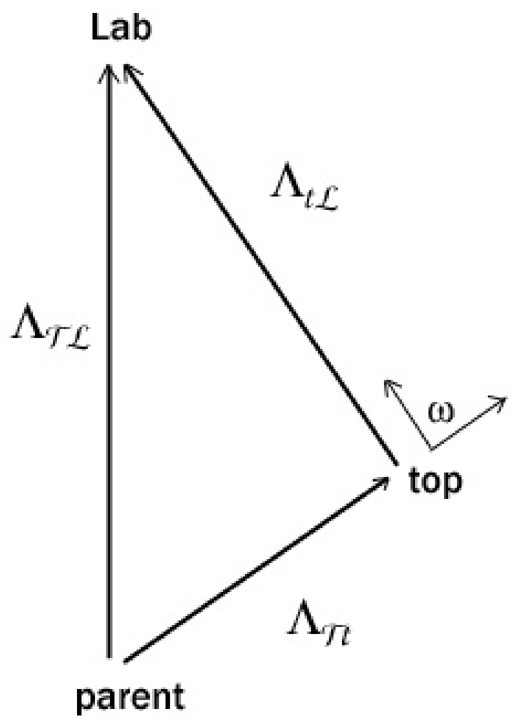


Net top quark polarization $\langle \mathcal{P}_P \rangle$ for purely chiral couplings ($b = 1,\ a = 0$).

- Red: fixed vector boson partner mass of 200 GeV
- Blue: vector boson partner mass of (top partner mass)−200 GeV
- Solid (dashed) lines: opposite- (same-) spin partners

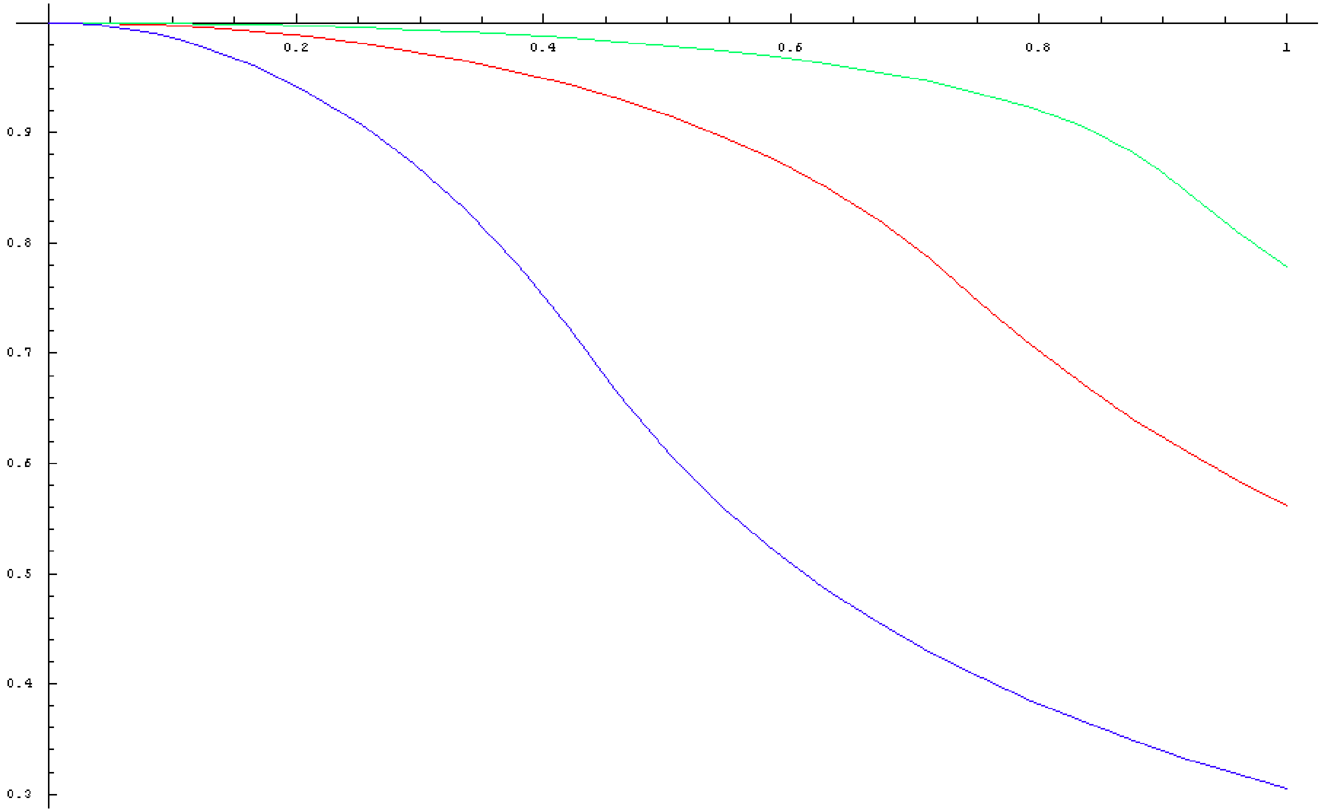
From production to detection

- **Cascades give net polarization $\langle \mathcal{P}_P \rangle$ along direction of motion in the *parent* rest frame. Not directly observable!**



  - Observable polarization is reduced: $\langle \mathcal{P}_D \rangle = \langle \mathcal{P}_P \rangle \cos\omega$
  - $\cos\omega$: calculable function of particle masses, production dynamics

Wigner suppression



- $\cos \omega$ **as a function of parent top partner boost** β
  - Red: $(M_T, M_V) = (500 \text{ GeV}, 150 \text{ GeV})$
  - Green: $(M_T, M_V) = (900 \text{ GeV}, 300 \text{ GeV})$
  - Blue: $(M_T, M_V) = (900 \text{ GeV}, 700 \text{ GeV})$

Conclusions

- **Top polarization is a valuable window into the chiral structure of new physics**
  - finite m_t complicates the story, but detailed quantitative predictions are possible
- **Polarization measurements in hadronic tops can be useful, especially if new physics contains stable invisible particles and decays through complicated cascades**
- **Also interesting are polarization-sensitive variables for collimated tops**
  - here, two simple variables; others possible
  - if b, W not separately discernible in collimated hadronic tops than more sophisticated techniques are necessary